SPAWAR Systems Center San Diego

Unmanned Systems Branch Code 2371

Advances in Autonomous Obstacle Avoidance for Unmanned Surface Vehicles

SPAWAR Systems Center San Diego

Unmanned Systems Branch

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OA in Marine Environment

Far Field:
Deliberative Path Planning

AIS Contacts
Nautical Charts
ARPA Contacts

Near Field:
Reactive Avoidance

Raw Radar
Stereo Vision
Nautical Charts
Monocular Vision
Millimeter Wave Radar
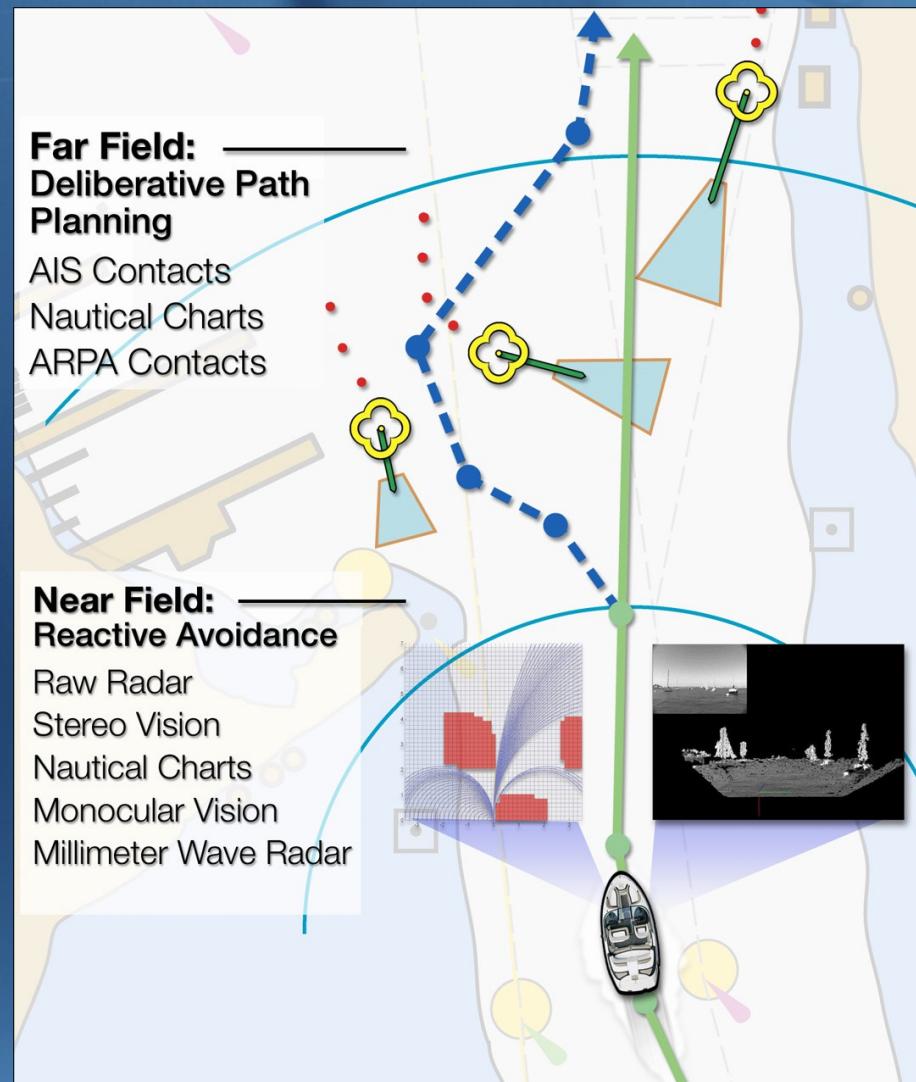
USV OA Software Architecture

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Chart Legend

Wireless →
Wired →
Planned →

Off-board
On-board

MOCU
(Operator interface at host ship)

Contacts and radar image

Recommended Route

Modified Route (4)

Initial route (1)

Initial route ok (3)

Path Planner

Navigator
(Global Waypoint Driver)

Global Pose

Modified route (5)

Initial route (2)

Contacts 0.33 Hz

Big Charts Low rate

Pose data

Navigator,
Path Planner, Chart Server,
Radar Server, Reactive OA,
MOCU

Planned Sensors

stereovision

Monocular vision

MMW radar

LADAR

Radar Server

Chart Server

Small Image 0.33 Hz

10 Hz Small Charts

Commanded Vel and TR

Tele-op cmds if no R. OA

Reactive OA

Tele-op cmds

Driver

Actuator cmds
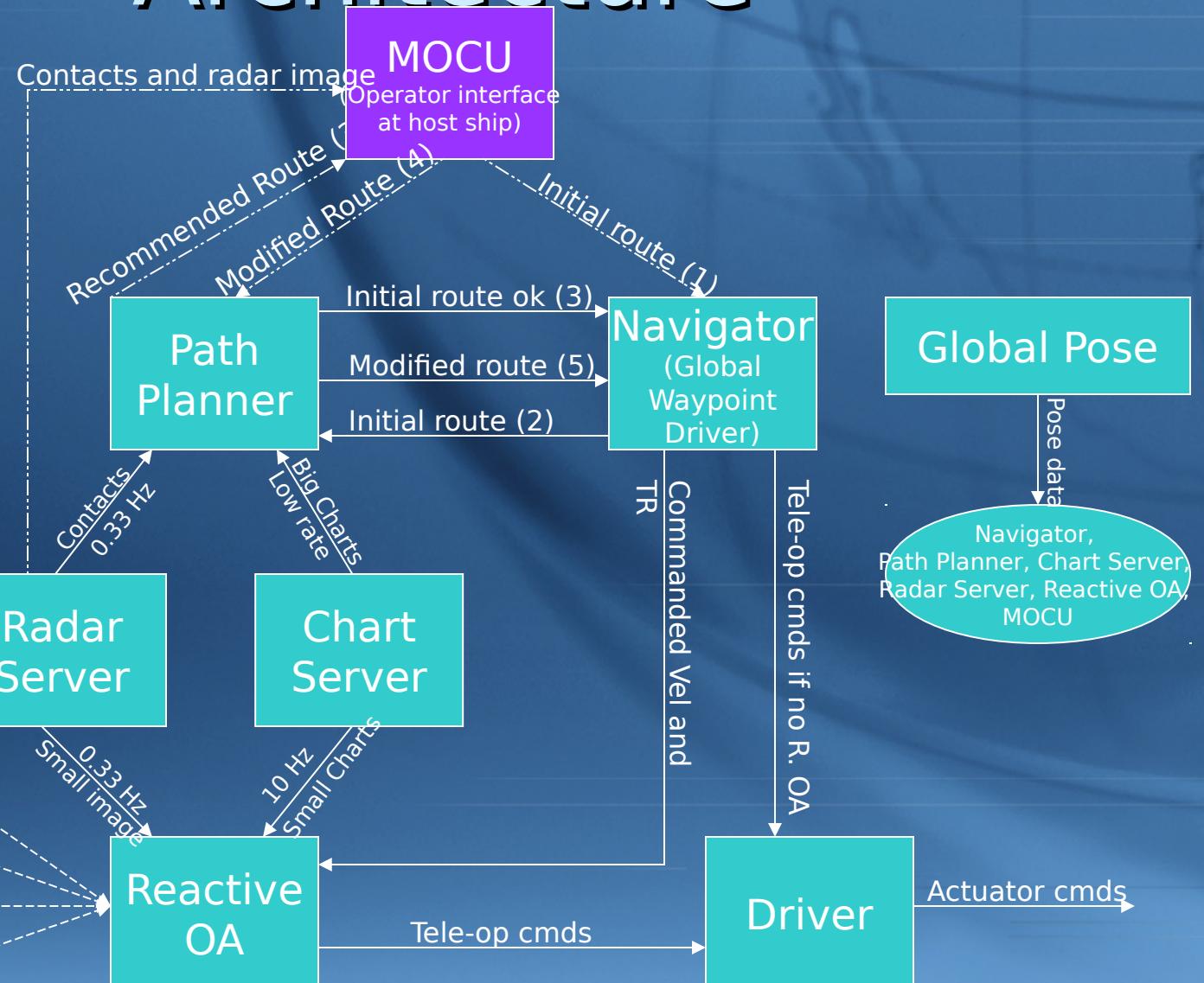
World Model

- **2-D occupancy grid obstacle map**
- **Two levels of abstraction**
  - Deliberative Map (far-field)
    - Digital nautical charts (DNC)
    - Automated radar plotting aid (ARPA) contacts
    - Automatic identification system (AIS) contacts
    - Future: Bathymetry data
    - Future: Host ship or shore side contacts
  - Reactive Map (near-field)
    - Radar
    - Stereo vision
   - Monocular vision
    - DNC
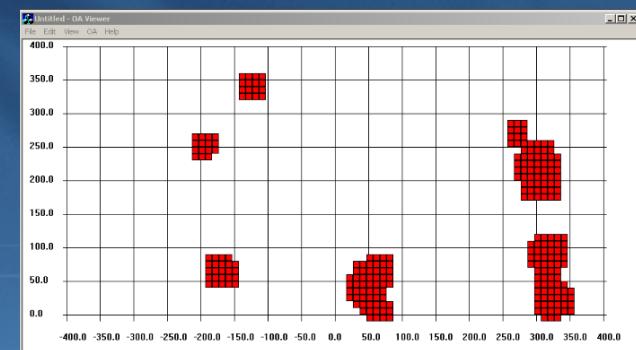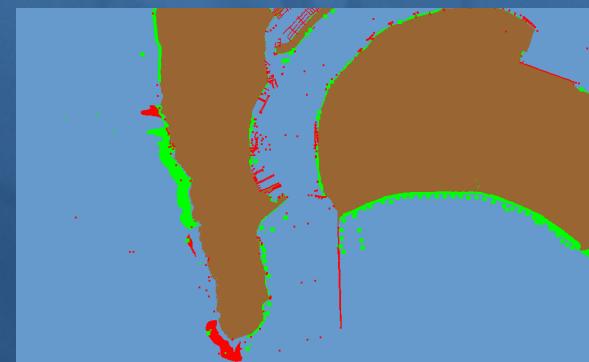
USV OA Requirements

- Plans around stationary and moving obstacles
- Minimal changes to the original route
- Fast (real-time)
- Operator has view and control of route at all times
- Follows navigation rules of the road

SSC SD Previous Work

- Far-field path planning to avoid stationary and moving obstacles
  - Nautical chart data
  - ARPA contacts
- Initial development to follow rules of the road
- Reactive OA for a ground vehicle platform

Deliberative OA: Path Planning

- A* search basis
  - Cost-focused exploration of grid space
    - Costs include path distance and proximity to obstacles
    - Obstacle-proximity cost variable provides means for setting a safety barrier around obstacles – different obstacles may have different safety barrier distances
    - Extendable to other costs (direction, shipping lanes, "soft" obstacles, route ETE, etc.)
- Path planning example northeast of Stockholm Sweden
  - 30m resolution grid
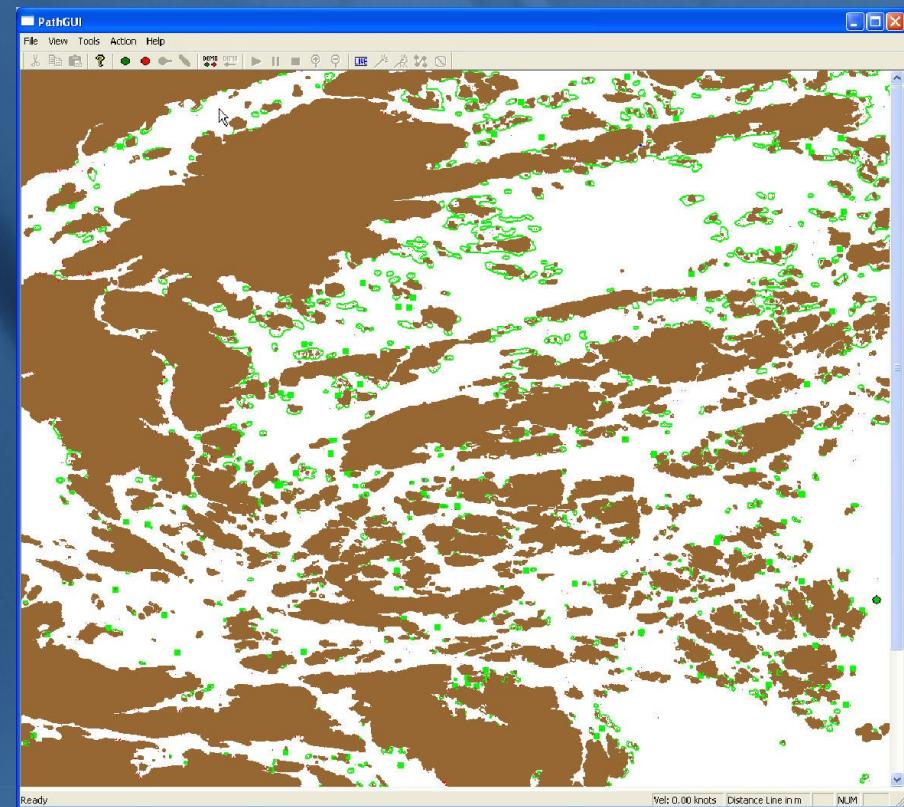
Maintain User-defined Route

- Maintain user-defined route unless obstructed
  - Path of route is generally important
- Revert back to user's route if obstruction no longer exists
  - Contact may slow or reverse direction or not even exist
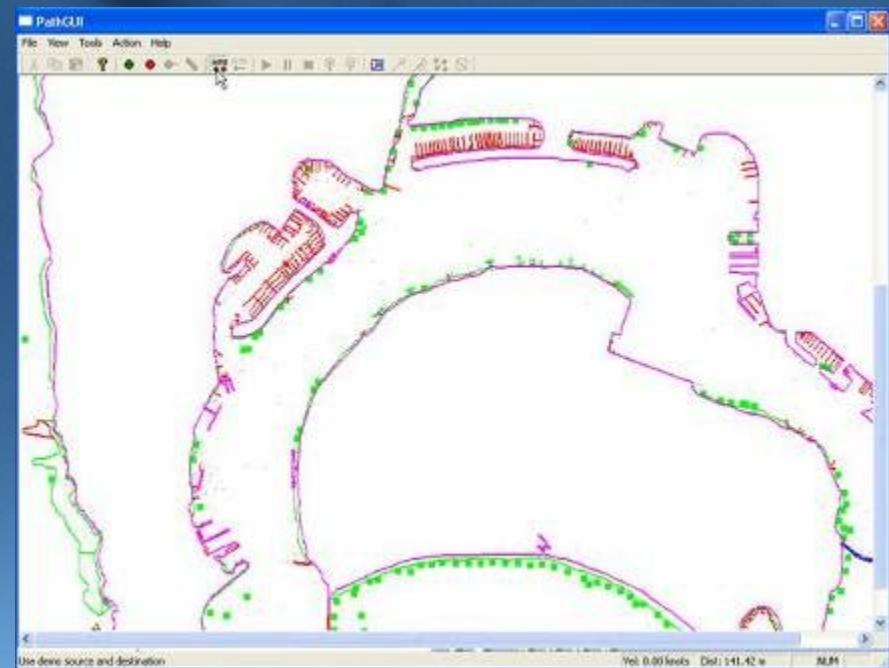
Rules of the Road

- Navigation rules as defined in 1972 International Regulations for Preventing Collisions at Sea (72 COLREGS)
  - Overtaking: the passing vessel shall pass on the port side of other vessel
  - Meeting: both vessels shall alter course to starboard so that each shall pass on the port side of the other
  - Crossing: the vessel that has the other on her starboard side shall keep out of the way and avoid crossing in front of the other vessel
- Rules are vague for angles and ranges for which they apply
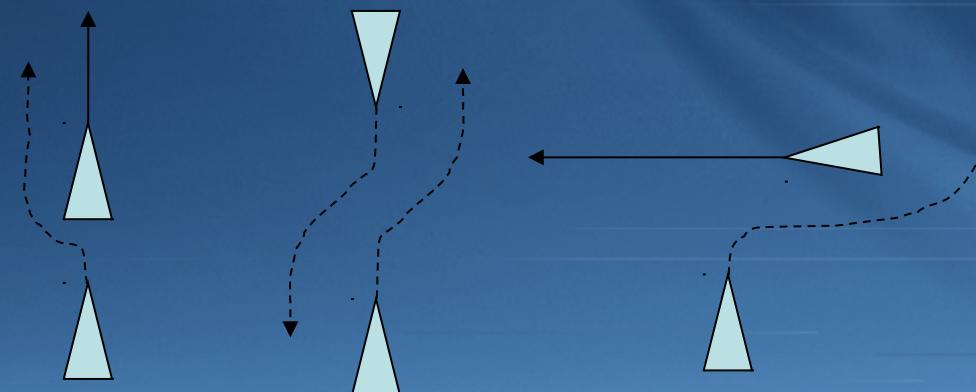
Overtaking
Crossing

Meeting

Rules of the Road: Projected Obstacle Areas

- Increase or decrease the projected obstacle area of a moving obstacle to bias the A* planner to mimic rules of the road

Average POA

Increase Port Angle

Increase Starboard Angle

Increase Ahead Distance

Increase Astern Distance

Rules of the Road

- Pass port-to-port when meeting head-to-head
- Follow direction of traffic flow
- Give right-of-way to other vehicles
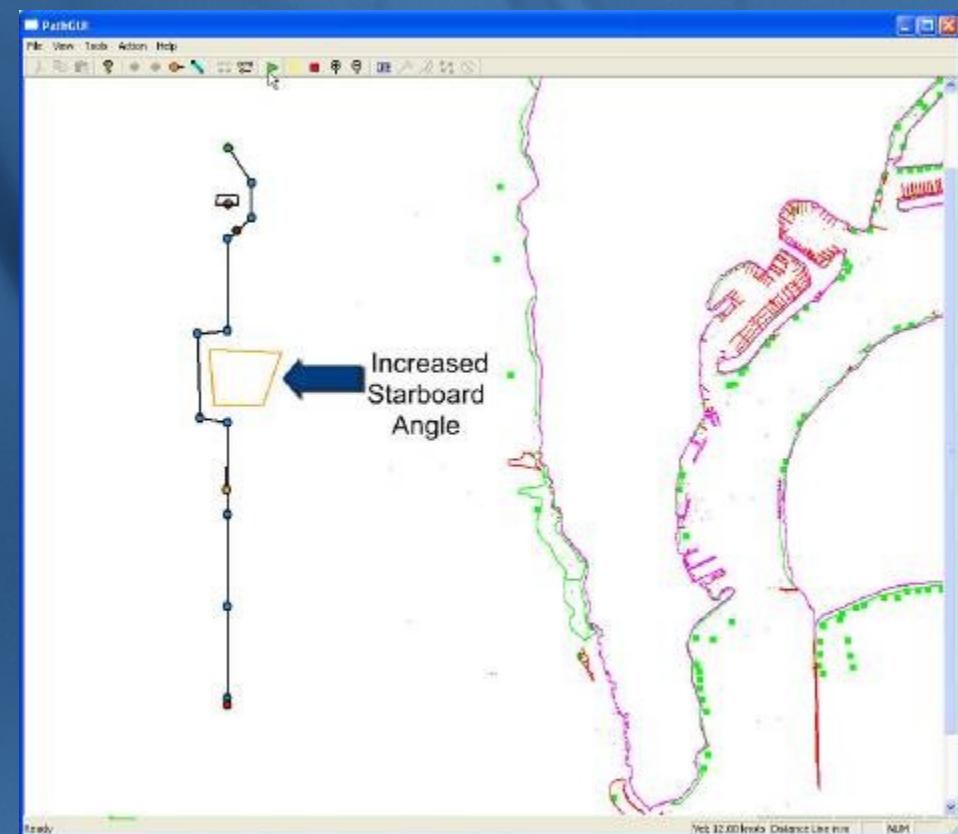
Rules of the Road: Markov Chain Monte Carlo Technique

- For a complicated multi-dimension cost function, standard search functions could get stuck in local minima and take a long time
- This technique uses a statistical model pseudo random sampling rule that keeps states better than the last


Graphics borrowed from Andrieu et al "An Introduction to MCMC for Machine Learning", Machine Learning 2003
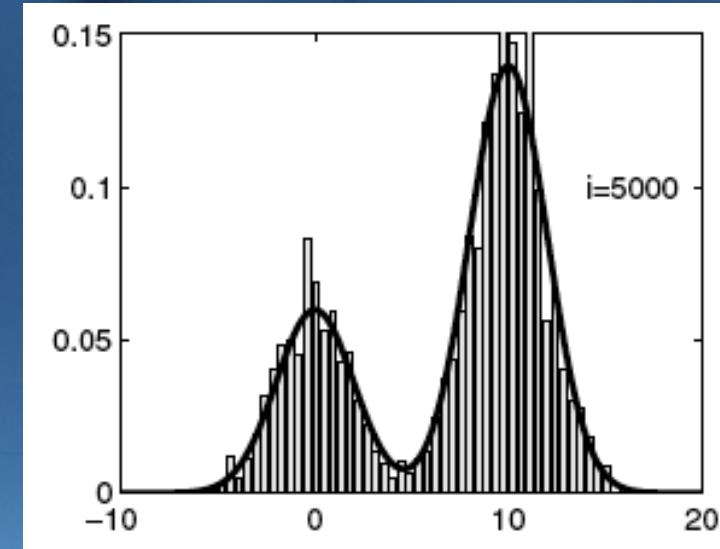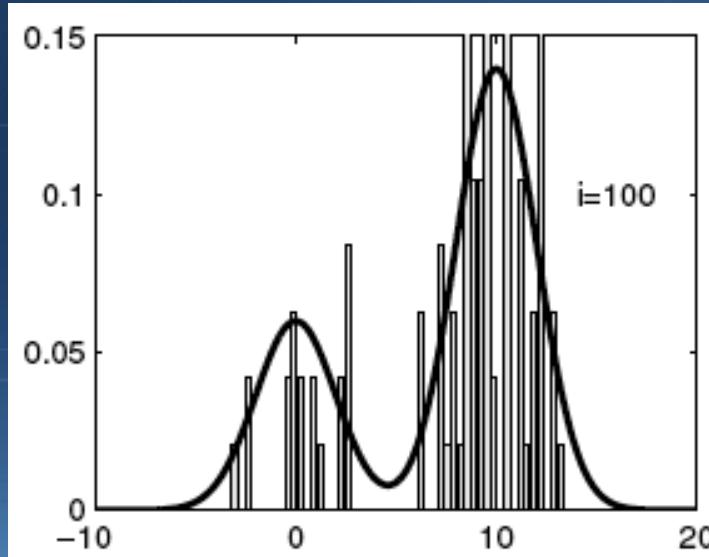
Rules of the Road: Examples
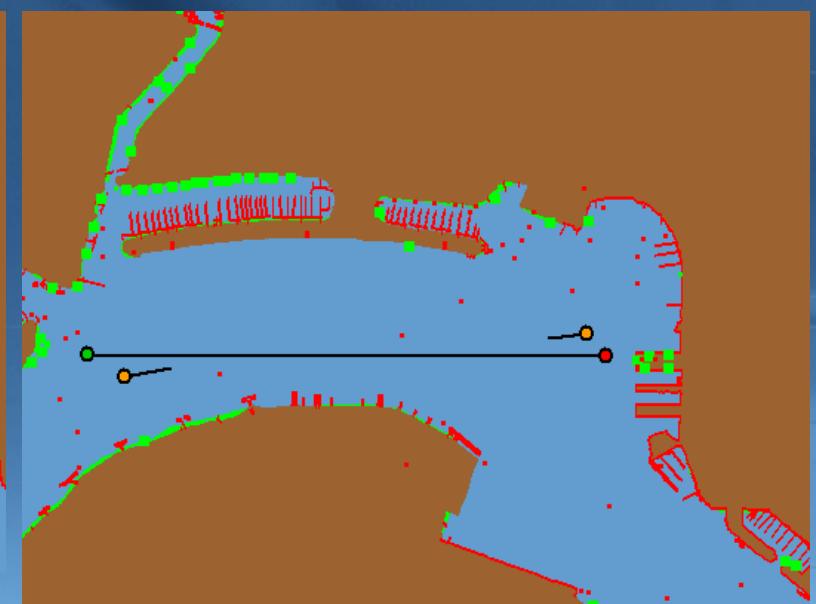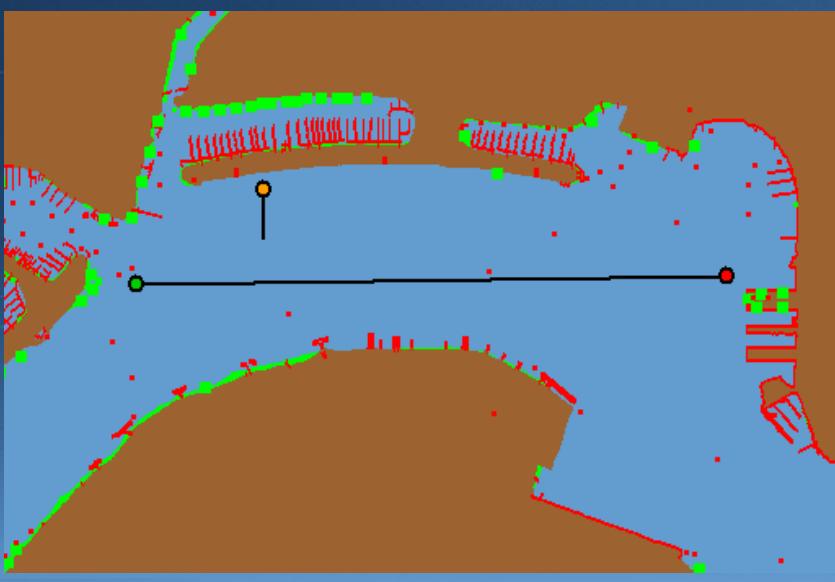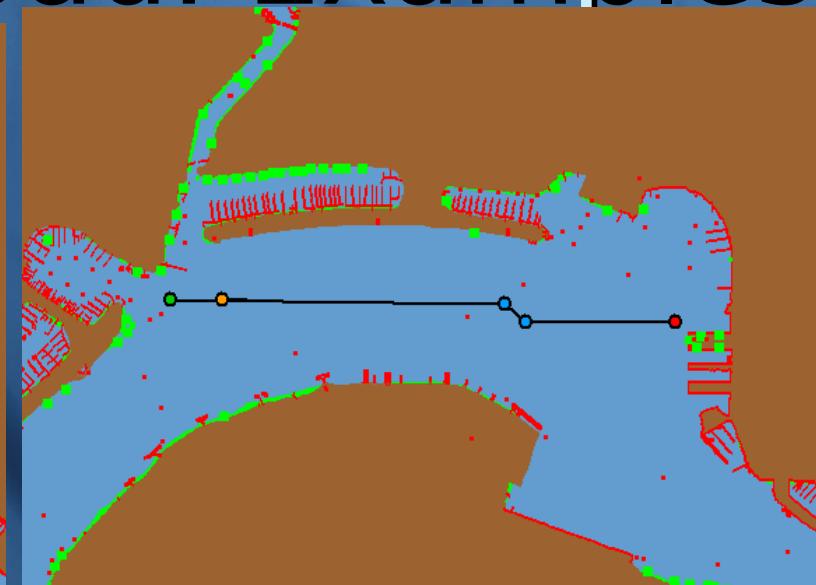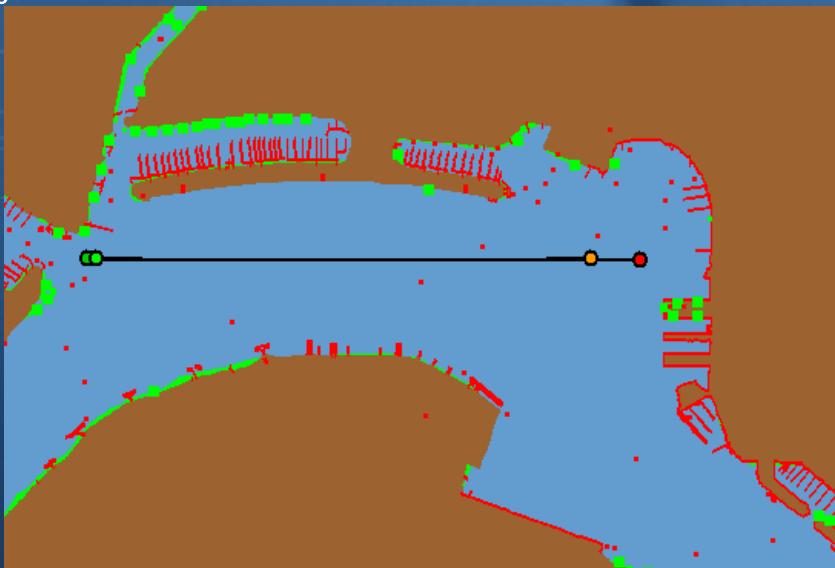
Target Tracking

- Uses deliberative path planner to chart course and velocity to track the target while avoid obstacles
- Future: add behavior to reactive OA to complete final action
    - Pull up on the port or starboard side of vessel
   - Cut-off and stop target
    - Trail behind
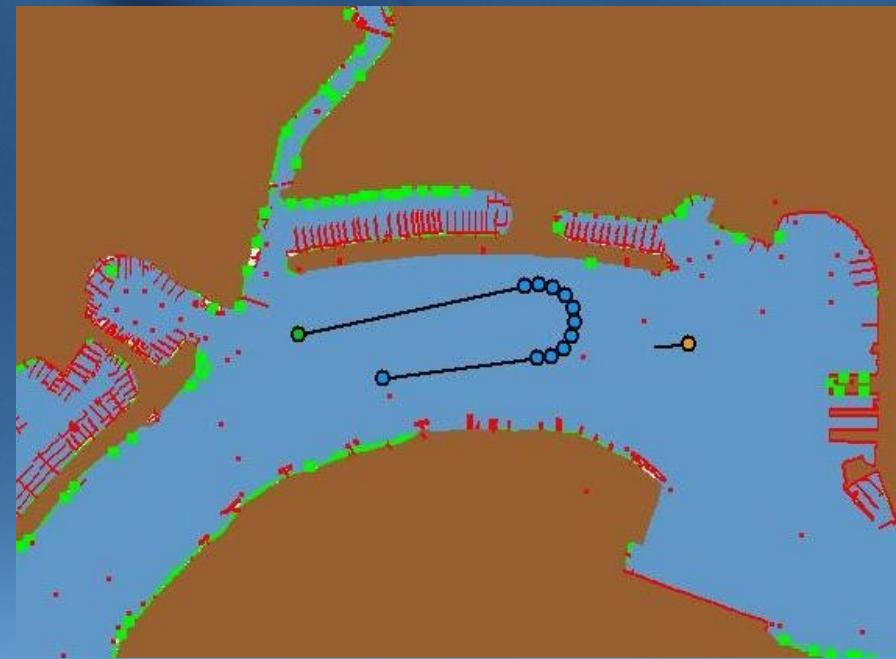
Radar – ARPA Contacts

- Networked marine radar
  - Xenex controller with a Furuno antenna
- Provides ARPA contacts
  - Position, speed and course of up to 100 contacts
- Issues
  - Data corrupted and contacts lost when USV turns at moderate rate
  - False contacts from shore
  - Distance to acquire small boats
  - Contact Acquire time

Contact ID: 81
Contact Name:
Course: 229°
Speed: 2.3 kts
CPA: n/a
Time to CPA: 00:01:22
Bearing: 98°
Distance: 611.7 yds
Target Status: Tracking
Type of Acquisition: Auto
Reported by USV
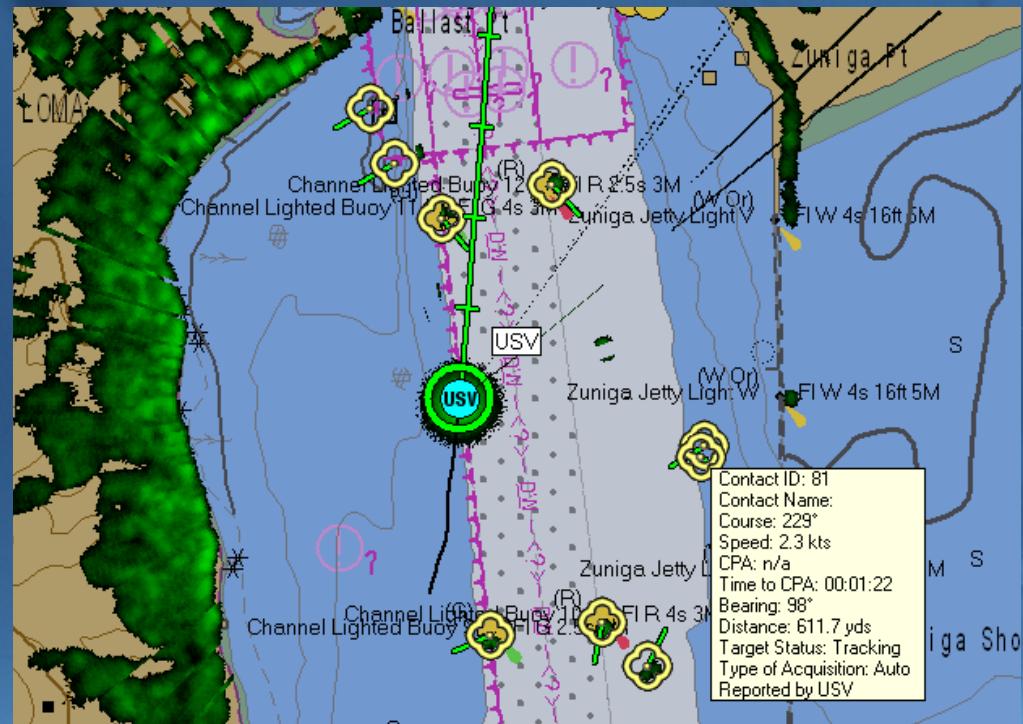
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Radar – Eliminate False Contacts From Shoreline
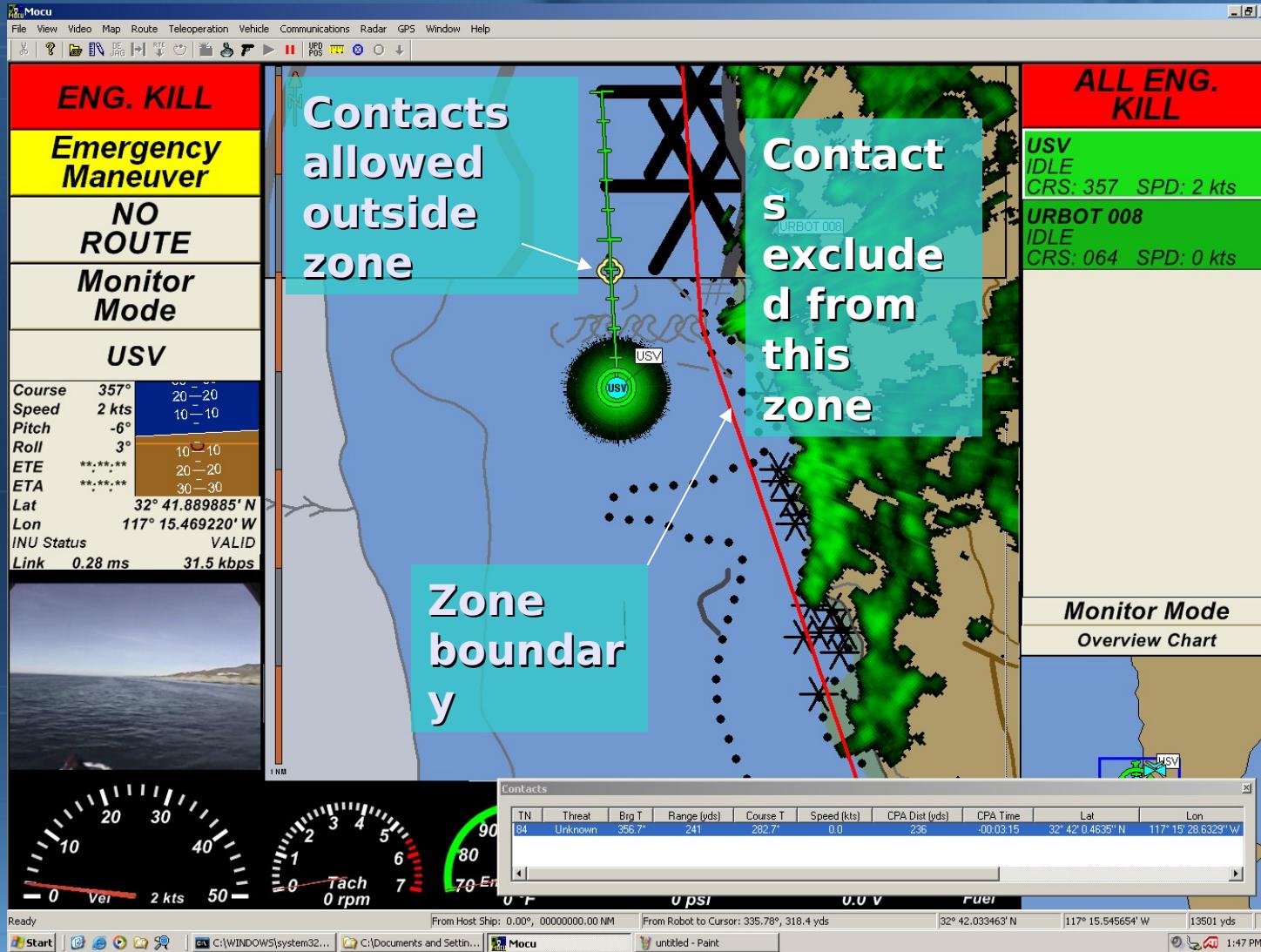
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Radar – Contact Acquire Time

Real World Path Planning Example

Reactive OA

- Real-time trajectory modification
- Modifies throttle and steering commands at the same rate as the navigation system
- Common occupancy grid map
  - Sensor data is fused into a common data space
- Behavior based
  - Path following, OA, target tracking, etc.
  - Very easy to add new sensors and new behaviors
- Operates in arc space
  - Selects best arc each cycle
    - Arcs are defined by a speed and turn-rate
    - Given the desired arc and speed a required turn-rate is calculated

Reactive OA

- Loosely based on CMU Morphin algorithm and the Distributed Architecture for Mobile Navigation (DAMN)
  - Distributed behavior based system
    - Multiple behaviors vote on desired actions
    - Votes scaled from 1 to -1
  - Obstacle avoidance behaviors vote for or against a fixed set of arcs
    - Arcs translate to vehicle speed and turn rate
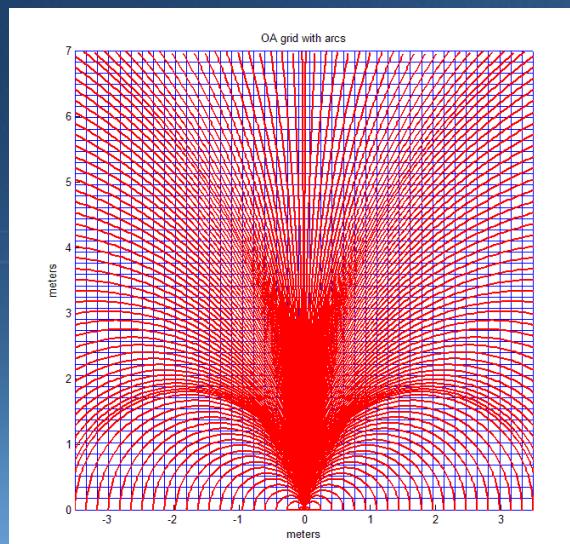
$$R = \frac{V}{\dot{\Theta}}$$

Reactive OA

- OA behavior votes against (0 to -1) arcs that are blocked
  - Vote is determined by the distance the vehicle could travel along that arc before it encountered an obstacle
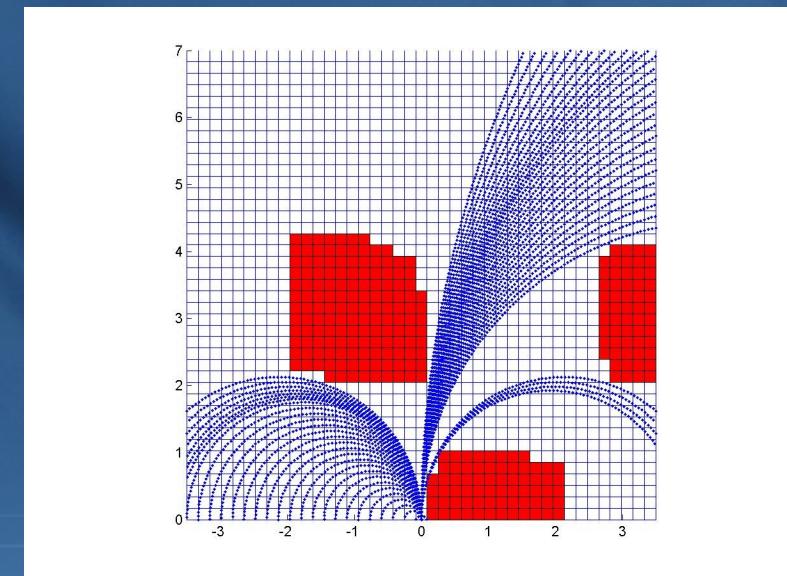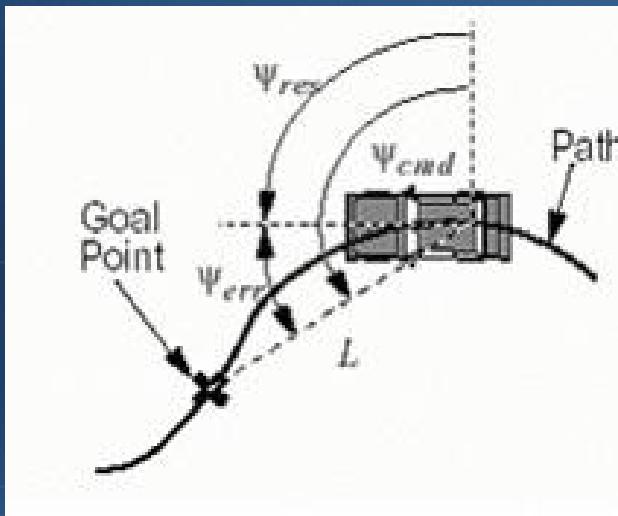

- Path following behavior votes for arcs (0 to 1) that are nearest the arc calculated by the waypoint navigation routine

Reactive OA

- OA behaviors and arbiter
  - Arbiter combines weighted votes from all behaviors
  - Arc with highest vote is selected and used to set the velocity and turn rate for that iteration
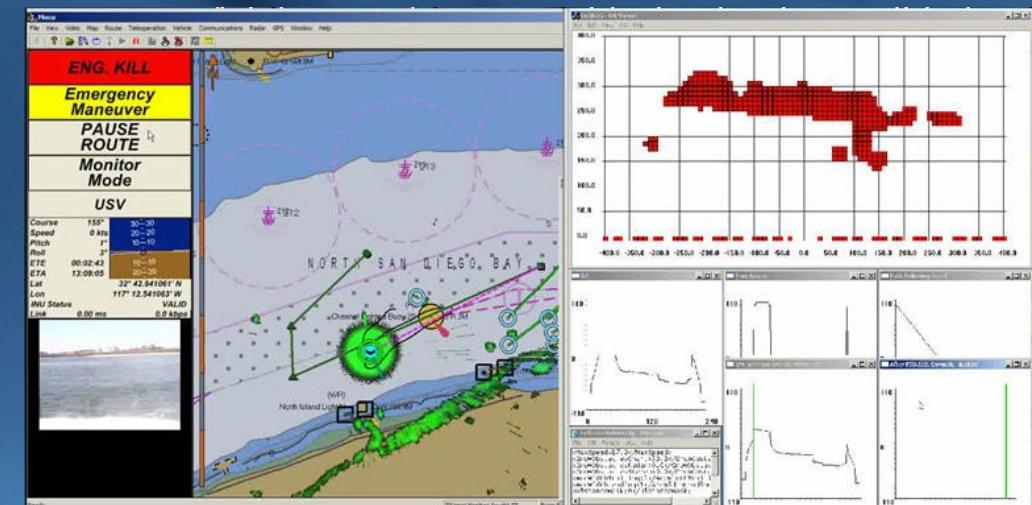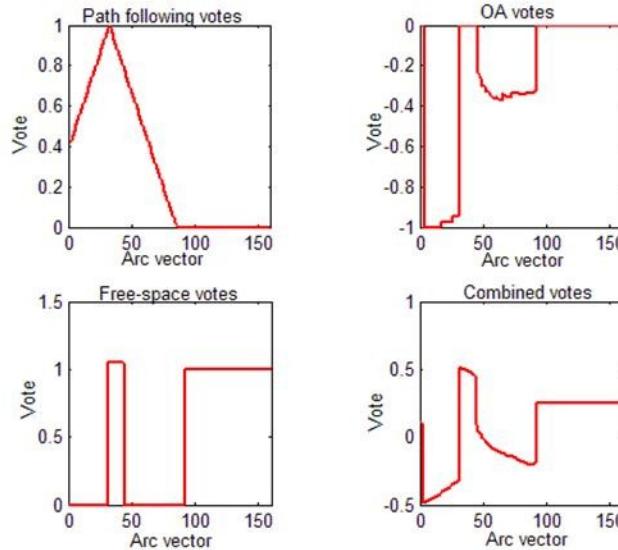
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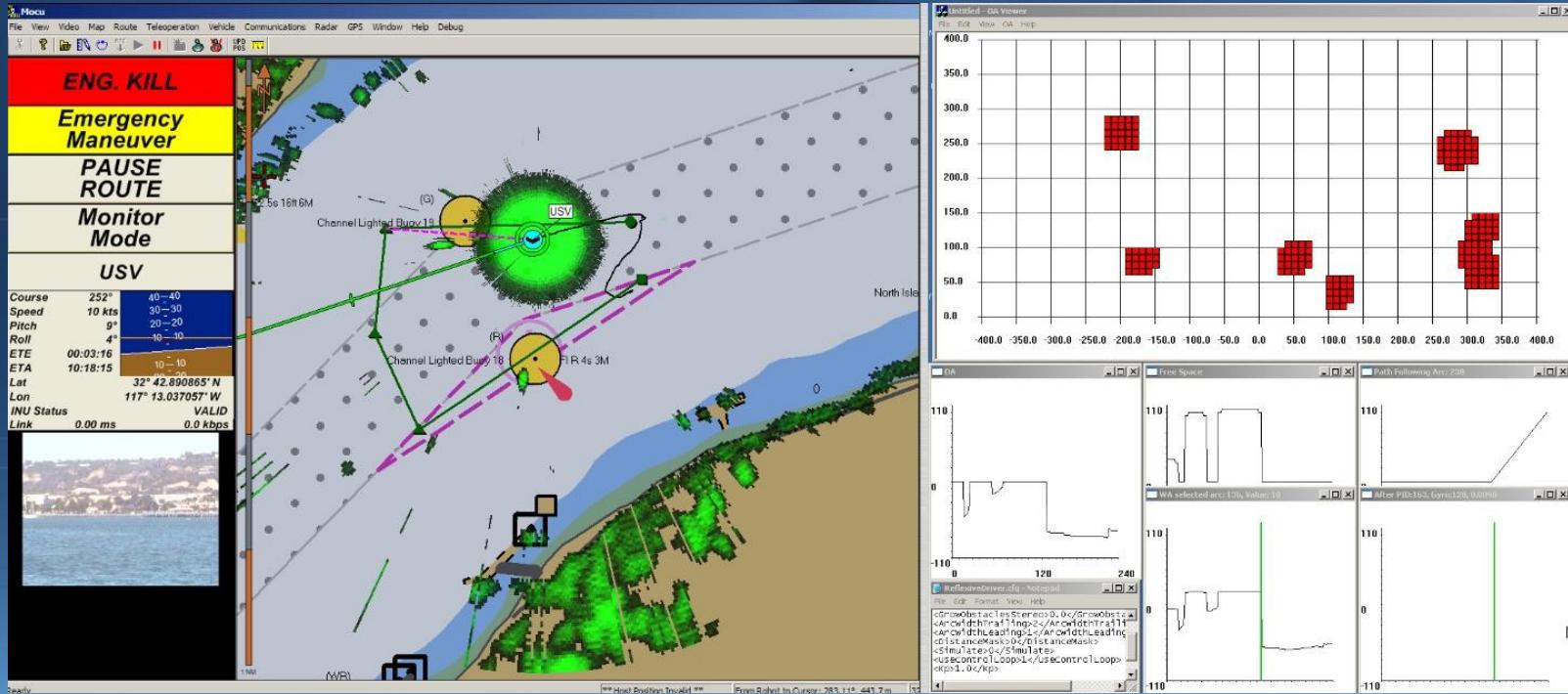
Reactive OA Sensors

- DNC data
- Raw radar
- Stereovision
- Monocular vision
- LADAR
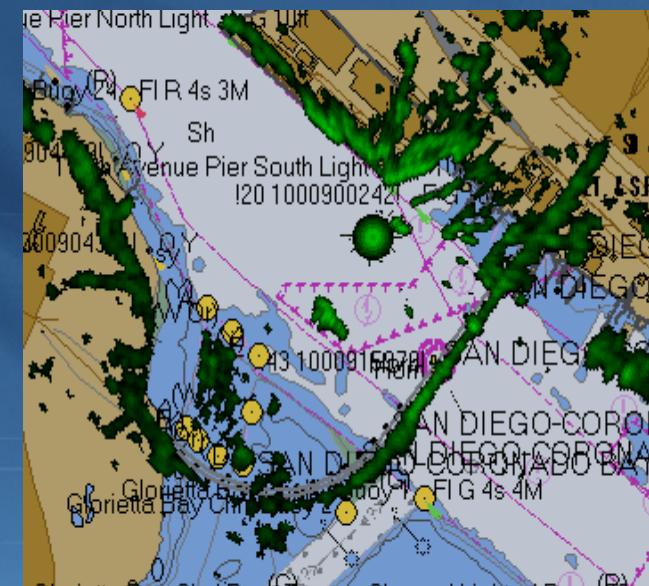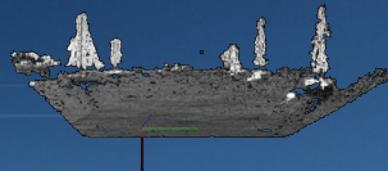
Reactive OA Sensors
Raw Radar

- Raw radar data from the USV radar server
  - 10Hz update rate
  - Small section of the radar image oriented heading up for the USV
    - Dead reckoned between radar updates
    - Converted from polar grid to Cartesian grid
 - Image processing performed to eliminate noise and extract useful data from center disk

Reactive OA Sensors
## Raw Radar – Conversion to Obstacle Map


Raw Radar image

Obstacle map centered on USV
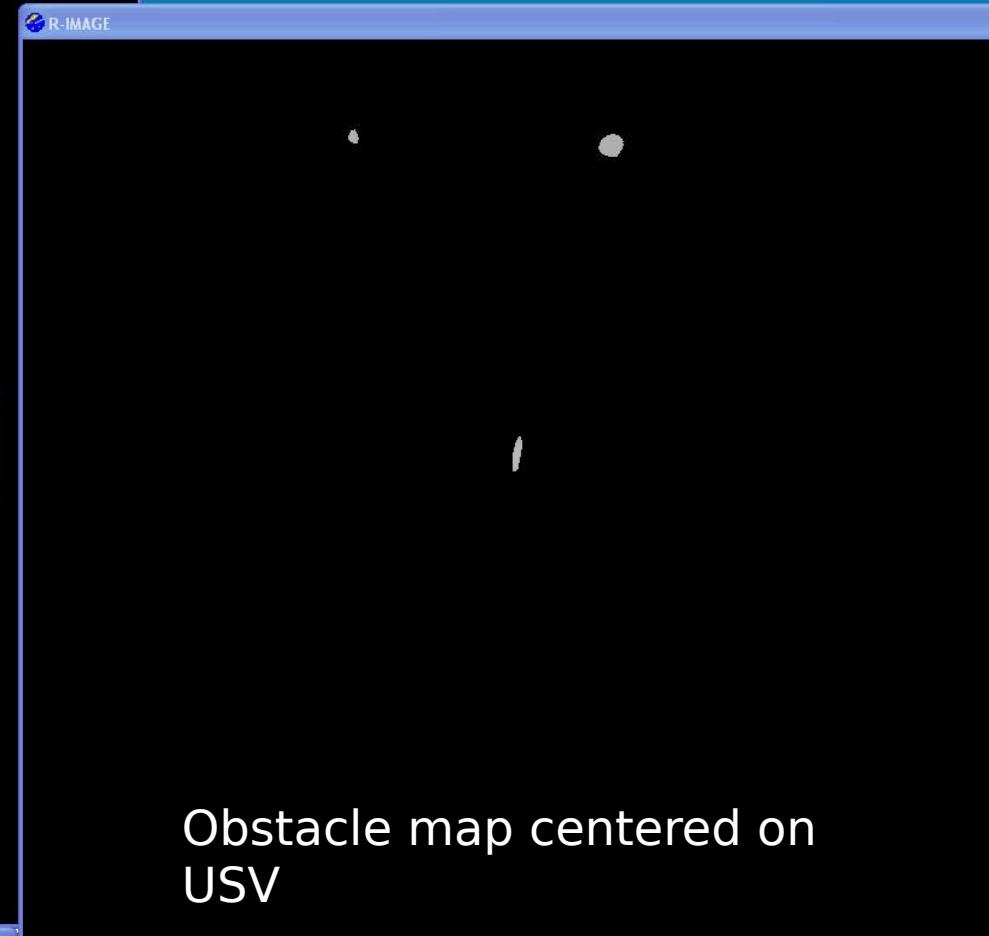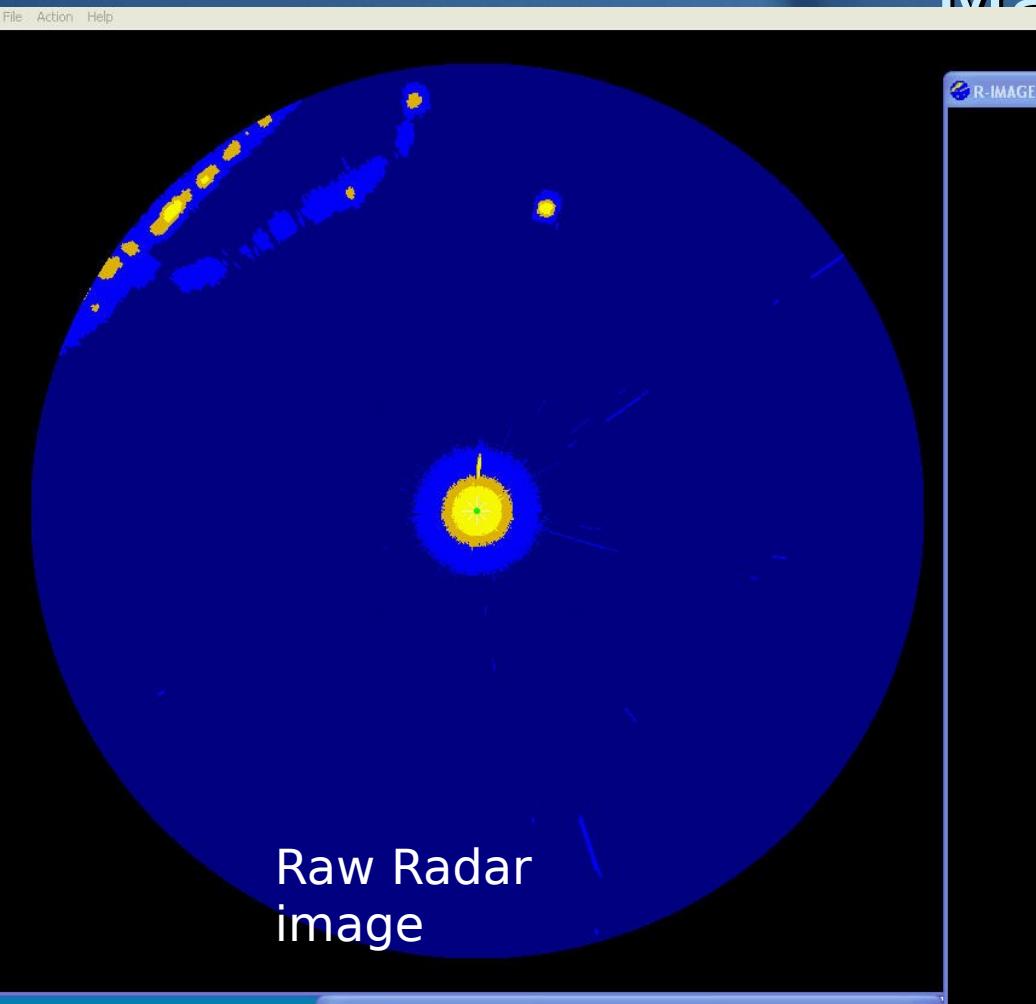
Reactive OA Sensors
Raw Radar – Center Disk
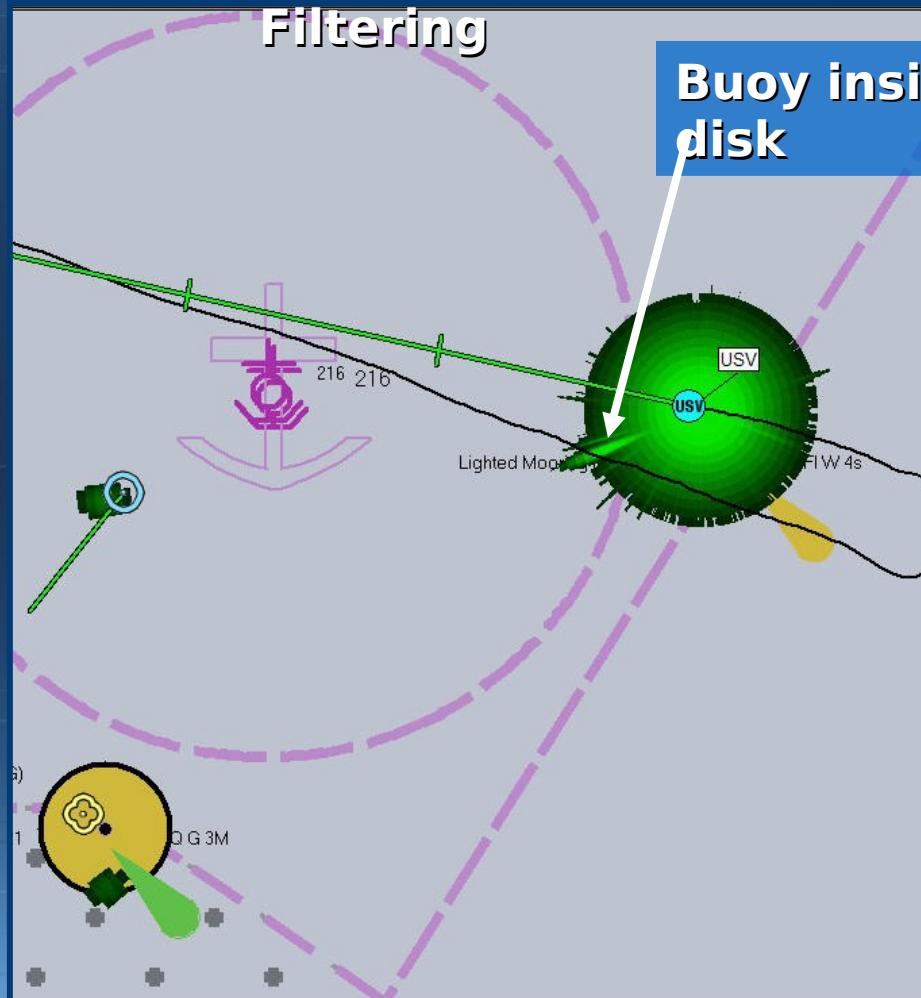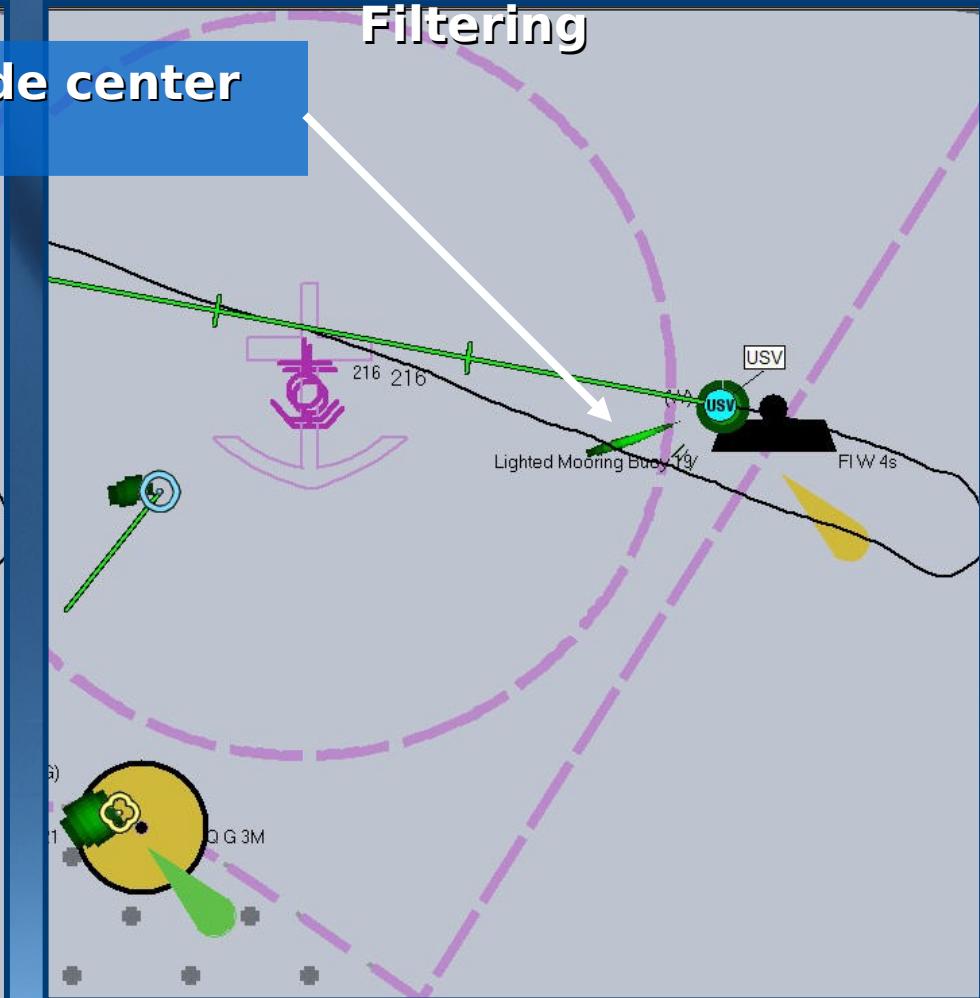
Reactive OA Sensors Stereo Vision

- Leveraging our work with the NASA Jet Propulsion Laboratory on stereo vision for our UGVs
- Collected stereo data on our USV at two different baselines
- Initial results look promising
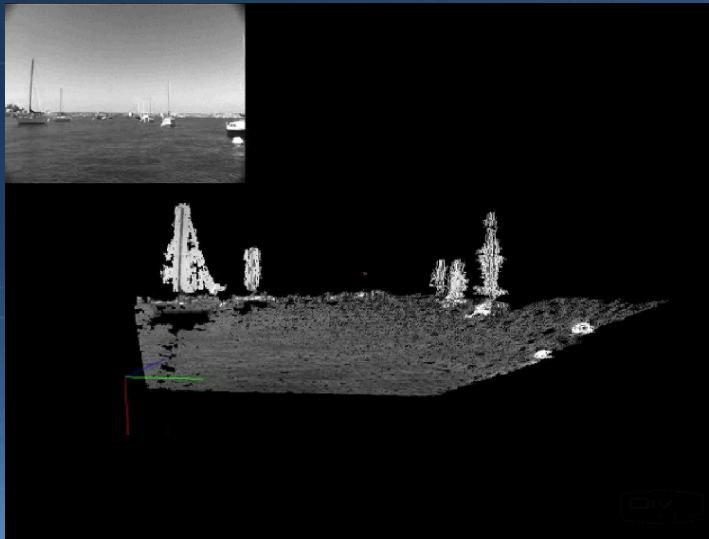
Provided by the NASA Jet Propulsion Laboratory
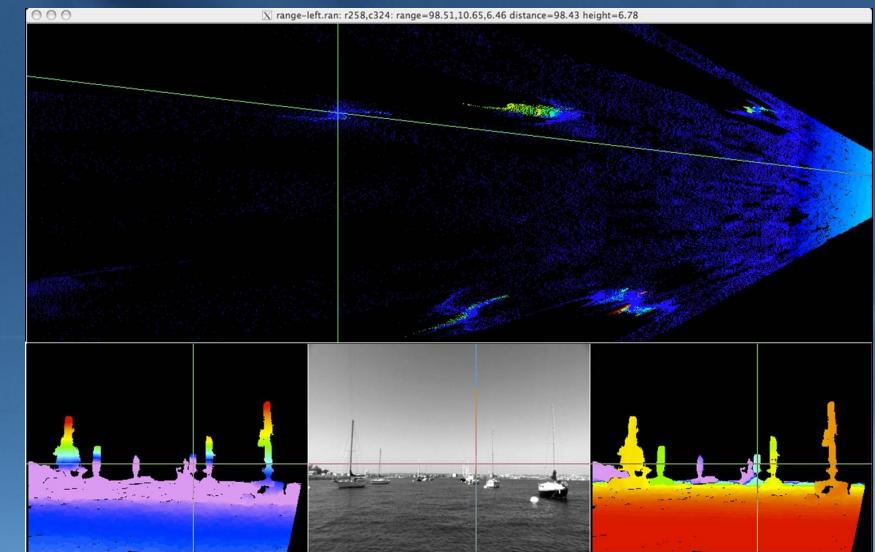
Provided by the NASA Jet Propulsion Laboratory

Reactive OA Sensors
Monocular Vision

- Detect obstacle on the water with a single camera
  - Color and texture segmentation, optical flow, etc.
  - Investigating both color and IR cameras
- Detect horizon line
  - Can obtain a rough estimate of range by determining how far below the horizon an obstacle appears in an image
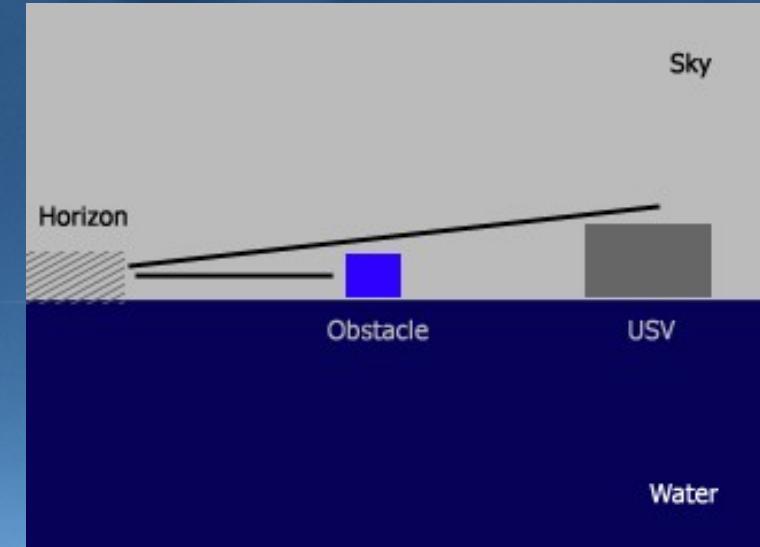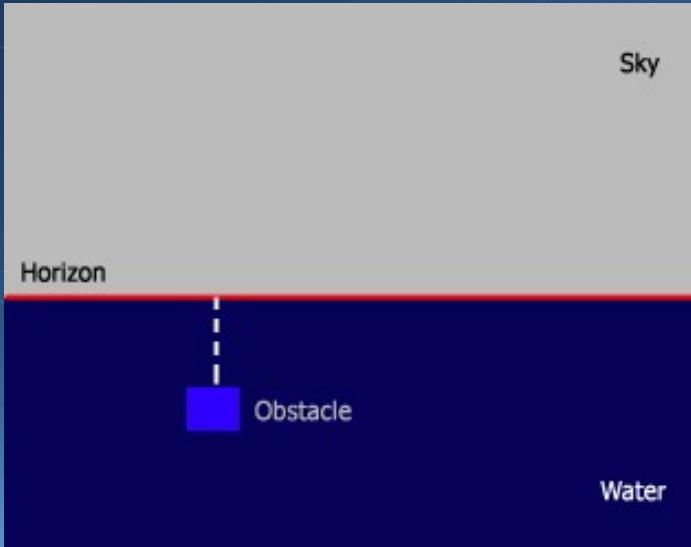
Reactive OA Sensors Monocular Vision

- Early results
  - 10 weeks of effort
- Horizon detection in presence of landmass
- Optical flow used to segment objects on water

Reactive OA Sensors Monocular Vision

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- Recent work to include range calculations

Conclusions

- Deliberative and Reactive techniques provide a robust OA solution
  - Tested in a real-world environment
- Sensor systems still need to be refined
  - Working with radar manufacture to improve performance
  - Developing more robust vision based obstacle detection techniques for small obstacles

Questions?

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